The Near Earth Object Surveillance Satellite: Mission status and CCD evolution after 18 months on-orbit

Brad Wallace
Robert (Lauchie) Scott
Michael Sale
Defence R&D Canada Ottawa, 3701 Carling Avenue, Ottawa, ON, K1A0Z4
Alan Hildebrand
Rob Cardinal
The University of Calgary, Department of Geoscience

ABSTRACT

The Near Earth Object Surveillance Satellite (NEOSSat) is a microsatellite designed to perform both Space Situational Awareness (SSA) and asteroid detection research. NEOSSat was launched on 25 February 2013 with a minimal software suite and after undergoing reduced system and environmental testing on the ground. The software required to obtain imagery and maintain stable pointing has since been uploaded to the spacecraft. NEOSSat has obtained imagery since June 2013 but has not achieved the pointing characteristics required to obtain scientifically useful data.

The collected imagery is being used to characterize the on-board CCD camera. Unexpected artefacts exist in the images and damage from high-energy particles impacting the CCD has produced increasing numbers of hot pixels. Early results from the mission (image examples, an image quality assessment) and the mission status will be discussed.

1. INTRODUCTION

The Near Earth Object Surveillance Satellite (NEOSSat) is an experimental microsatellite jointly funded, procured and operated by the Canadian Space Agency (CSA) and Defence Research and Development Canada (DRDC) [1]. NEOSSat was built for three main missions:

1) To be the first demonstration of the CSA's Multi-Mission Microsatellte Bus (MMMB) specification,
2) to detect and track potentially hazardous asteroids inside Earth's orbit, and
3) to demonstrate the ability of microsatellites to perform militarily useful missions by conducting research in space-based space surveillance.

The asteroid detection mission is referred to as the Near Earth Space Surveillance (NESS) mission. The space surveillance research mission is referred to as the High Earth Orbit Surveillance System (HEOSS). To perform its observing missions, NEOSSat is equipped with a small optical telescope with a light rejection baffle and a CCD camera system. The spacecraft was launched aboard an Indian PSLV launcher in February 2013.

The goal of this paper is twofold. The first purpose is to provide a snapshot of the state of the spacecraft after 18 months on orbit. The second is to present a characterization of the CCD camera and electronics.

We begin with a brief overview of the requirements for NEOSSat followed by a history of NEOSSat's development and testing, focusing on items relevant to its scientific potential. The on-orbit characteristics and evolution of the camera will be presented before concluding with a summary of the current state of the spacecraft and the science plan.

2. NEOSSat REQUIREMENTS

Due to the three different missions for NEOSSat, the requirements ranged from details such as the number of power lines in the satellite to more complicated items such as the amount of stray light to be rejected by the baffle in a variety of observing scenarios. The reader who is interested in the full range of requirements is directed to [2]. For the purposes of this section we shall review the requirements relevant to the scientific potential of the imaging system.

In **Table 1** we list some of the spacecraft and imaging system requirements needed to obtain the data required by the two science teams. More details about the satellite and its missions can be found in [1][2][3].

Table 1: Some requirements relevant to NEOSSat science

Quantity	HEOSS Requirement	NESS Requirement
Sensitivity	Detect objects with M_V=13.5, moving at a relative angular rate of 60 "/s, in a one second exposure	Detect objects with M_V=19.5 in three out of four 100s exposures.
Field of View	> 50 arcminutes square	
Pixel Size	3 arcseconds square	
Optical Point Spread Function size	<1.5" measured at full-width half-max	
Pointing Stability	0.5 arcseconds rms over 100 seconds	
Image transfer time	< 15 seconds	

3. HISTORY OF NEOSSat

The current status and capability of NEOSSat are the result of decisions taken throughout the history of the project. Some of these decisions are discussed briefly here.

Telescope design

The optical telescope design is based on the MOST (Microvariability and Oscillations of STars) space telescope [4]. The telescope is a 15cm diameter Maksutov Cassegrain design with two identical E2V frame transfer CCDs sharing the focal plane. One CCD is used for science purposes, while the other CCD is used as a star tracker to maintain the high pointing stability required of NEOSSat. The choice of a MOST-derived telescope design was based on a desire to a) minimize expenses while b) reducing mission risks by using a flight proven telescope design. The design of the telescope differs from MOST's in that it includes an internal shutter (for sun protection) and field-flattening lenses to improve image quality across the focal plane.

CCDs

In another attempt to minimize costs a decision was made to use the flight-spare CCD's from MOST. These flight spares had been used to test the design of MOST's imaging electronics and to test the behavior of the CCDs under the expected on-orbit radiation environment. A technical assessment of the CCD's was conducted and concluded that the CCDs were still acceptable for the science team's needs.

Imaging System Testing

The telescope optics were tested separately from the CCDs and Read-Out Electronics (ROEs). Due to delays in the design and build of the spacecraft ROEs, the CCDs were originally tested using a temporary, MOST derived, ROE. The final ROEs were inserted into the testing late in the project.

The telescope, baffle and imaging electronics (CCDs and ROEs) were integrated only a short time before the imaging system as a whole was itself integrated into the spacecraft. No end-to-end testing (e.g. of a real or simulated starfield) of the fully integrated imaging system was conducted on the ground. The CCDs and ROEs were tested during the environmental testing campaign. The testing of the entire imaging chain is currently being conducted on-orbit.

Spacecraft Software

The development of the spacecraft Flight Software (FSW) significantly lagged the development and testing of the spacecraft. The development lag caused the full FSW not to be available in time for launch. Due to the costs and delay involved in obtaining a second launch it was decided to launch the spacecraft with only the minimum FSW needed to keep the spacecraft safe and able to receive commands and software updates from the ground.

The portion of the FSW needed to obtain images was delivered in June 2013, almost 4 months after the launch of the spacecraft, with the first dark images taken shortly thereafter. Delivery of the software needed to maintain spacecraft pointing stability was developed in an evolutionary manner, and the first images with the required stability were taken in mid-June 2014. Development and testing of the spacecraft attitude control system (ACS) has continued, with the focus currently being on the ability to consistently slew the spacecraft to any point on the sky and quickly reach the pointing stability required to obtain scientific imagery.

Full spacecraft testing

NEOSSat underwent environmental testing from September to December 2012. During the testing, several issues were detected that required minor rework of either the spacecraft or the testing equipment. These unanticipated delays resulted in a reduced testing campaign and acceptance of the associated risk.

4. CCD CHARACTERIZATION ON-ORBIT

The first engineering images were obtained from NEOSSat in mid-June 2013. These images were obtained with the camera shutter closed ("dark" images). An example image is shown in **Fig. 1**.

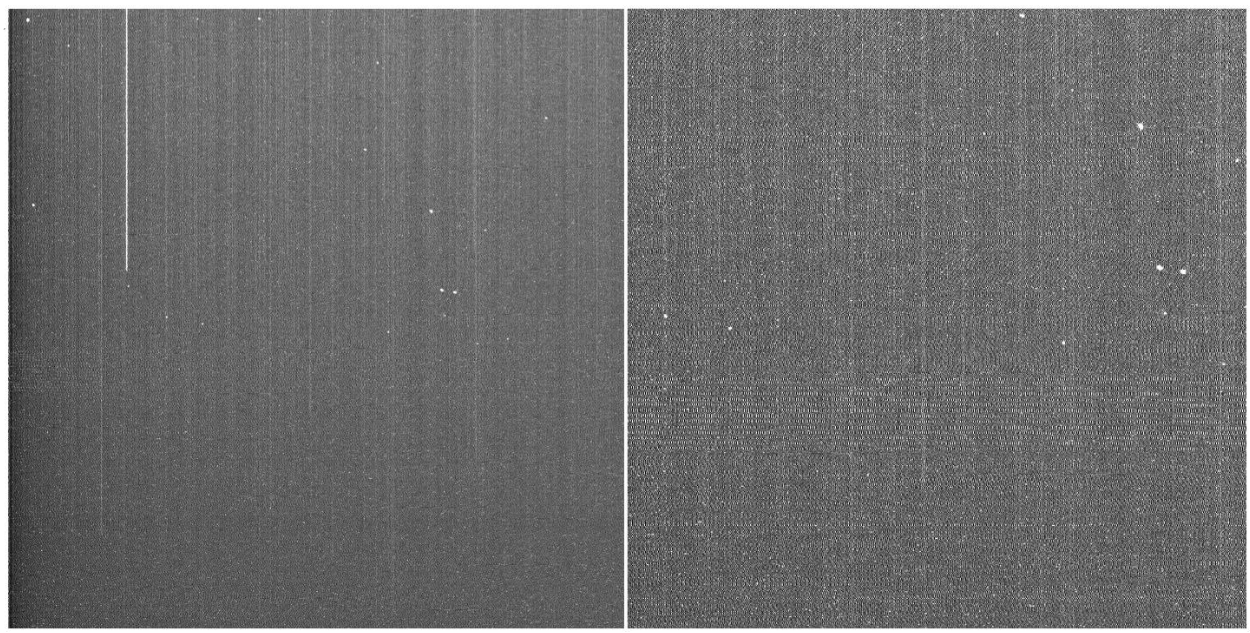


Fig. 1: An example dark image obtained from NEOSSat science CCD in mid-June 2013. On the left is the full image, while on the right is the inner quarter of the same image expanded to show detail.

A number of image artefacts were immediately noted:

- A bright, vertical line (a “bad column”) on the left side that goes from the top to almost half way through the image
- Faint vertical lines across the image that get brighter toward the top of the image and create a brightness gradient from bottom to top
- A number of small point-like objects. These are cosmic ray strikes and will not be discussed further here. The interested reader is directed to [1]
- A number of individual bright, or “hot”, pixels
- A number of relatively bright horizontal bands that are each several rows thick

The relevant characteristics of the CCD are discussed in more detail below.

Bad Columns

The science CCD has a pair of bright partial columns located adjacent to each other on the left of the CCD. The pixel values in this region are consistently and significantly higher than their surrounding pixels values, but are neither saturated nor constant along the column. These bright columns are a permanent feature of the CCD and are dealt with in post-processing. They will not be discussed further here.

Hot Pixels

Hot pixels can be intrinsic to the CCD, and can also be created as a result of cosmic ray impacts with the CCD. As a result, the number of hot pixels is expected to increase with time on-orbit. A simple assessment of the cumulative damage to the CCD can be done by monitoring the increase in the number of hot pixels as a function of time.

A hot pixel can be defined as a pixel, with a consistently high value across all images, that has a vanishingly small chance of being created by thermal means. The imaging sections of NEOSSat’s CCDs are 1024x1024 pixels in size so a reasonable definition of a “hot pixel” is a pixel having an intensity that has less than a 1-in-a-million chance of being induced by thermal noise. This corresponds to an intensity value roughly 5 times the rms above the mean.

For the purpose of deriving a rough measure of the evolution of damage to the CCD we identified two sets of images which were obtained with the CCD at roughly the same temperature as the dark images obtained in the first imaging session in mid-June 2014; a total of three image sets were thus analyzed. The temperature constraint was included because the brightness and number of hot pixels is highly temperature dependent.

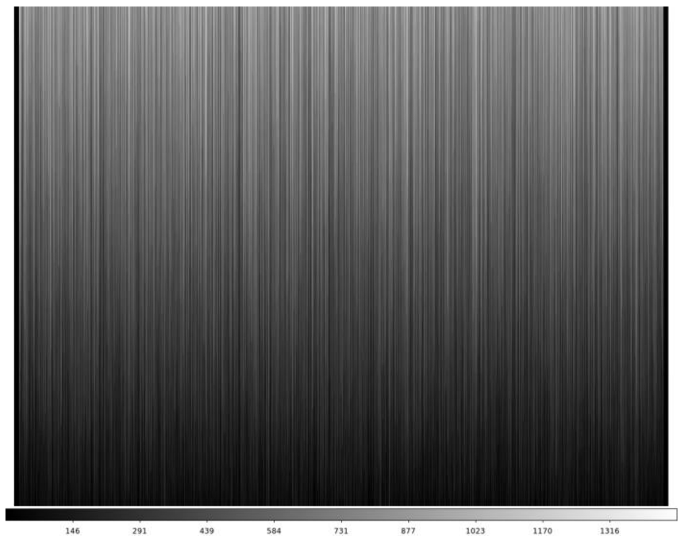
The first image set consisted of dark images, while the other two image sets were taken with the shutter open, but with the spacecraft (and thus telescope boresight) moving rapidly on the sky. The characteristics of the images are shown in **Table 2**.

Table 2: Characteristics of image sets used for hot pixel analysis

Days after launch	**Number of images median filtered**	**Type of images**	**Number of Hot pixels in inner 512x512 region**	**Percentage of image with hot pixels (>5 x rms)**
106	8	Dark	1044	0.40
186	4	Light	1736	0.67
501	5	Light	3471	1.32

Cosmic rays and sky emission were removed by median filtering each set of images. Fitting and subtracting linear backgrounds for each column, thus flattening the image background, removed the faint vertical lines in the median filtered image. Regions with bad columns or residual emission from bright stars were removed in all three images using a common mask. The rms noise was determined iteratively for each flattened image and the cutoff value for hot pixels was chosen as 5 times the rms of the noisiest flattened image. The number of pixels with intensity above this cutoff level were then determined for each image and the results are also tabulated in **Table 2**.

The growth rate of bad pixels is well fit by a linear function. The function suggests that the CCD had roughly 2000 hot pixels (0.2% of the pixels) at launch, and that 25 new hot pixels are created each day. The CCD currently has more than 1% of the pixels being "hot," a number which the team hopes to reduce by intentionally heating the CCD from its operating temperature of roughly -20C to a temperature +30C for a period of several hours (a process called "annealing" [5]).



Vertical Striping

Figure 2: A simulation of the striping that would result from a hot pixel distribution, similar to the distribution in the imaging area, under the CCD mask.

Vertical striping is seen in every column and appears as an enhanced background upon which other features sit. The striping often begins at a discrete pixel in a given column, but the intensity of the stripes always increases towards the top of the images. The rate of intensity increase varies from column to column.

It is suspected that this striping is related to hot pixels under the transfer mask of the frame transfer CCDs. After each exposure the charge collected in the imaging area is shuttled quickly to an area, equal in size to the imaging area, with an opaque cover so that the pixels no longer collect charge due to impinging light. A full image on NEOSSat takes 13.4 seconds to read out from this masked area, and each image pixel continues to collect charge due to thermal effects of the "masked" pixel on which it dwells. The CCD is read out row-by row, so the pixels at the top of the image will collect more of this "extra" thermal charge than those at the bottom, creating a natural gradient in the background.

This "extra" charge accumulation is thought to be exacerbated by the presence of hot pixels (presumably also caused by cosmic ray damage, as in the imaging area) under the mask. While a given image pixel dwells on a masked hot pixel it will accumulate charge (above and beyond the thermal noise) due to that hot pixel. As the CCD image is shifted down row-wise during readout, pixels higher up in a particular column will collect charge from more hot pixels in that column, and as such will exhibit increasing background levels towards the top of the image.

This hypothesis was tested by simulating the striping that would result if the hot pixel distribution seen in the imaging area was duplicated under the masked area. The resulting image is shown in **Figure 2**. The intensities and slopes of the resulting vertical stripes are consistent with the observed striping, and the stripe distribution is qualitatively similar to that seen in actual imagery.

Since the imaging area gains ~25 hot pixels per day, the masked area is likely to gain a similar number. As such, the stripes in the imagery will evolve with time. The annealing discussed above will likely help reduce the intensity of the stripes since it will reduce the number of hot pixels both under the CCD mask and in the imaging area.

Dark Current

Dark Current is charge accumulated by image pixels due to thermal affects within the CCD. The dark current is simply measured by taking dark images of various exposure lengths, and measuring the average background level on each image. The increase in the background level as a function of time yields the dark current.

The dark current was measured both before launch and on-orbit. Taking temperature dependencies into account, the measured on-orbit dark current is consistent with the measured pre-launch dark current. Both measurements are also consistent with the manufacturer's specifications [6]. We are planning to compare these values to measurements we plan to take at the spacecraft's end-of-life.

Interference and image noise

Immediately after the first images were obtained it was noted that the image noise was roughly three times higher than measured on the ground and expected on-orbit. This was consistent with the appearance of prominent horizontal "bands" of increased brightness that appeared in random positions across the images. Even in regions outside these bright bands, however, the measured noise was still significantly higher than expected.

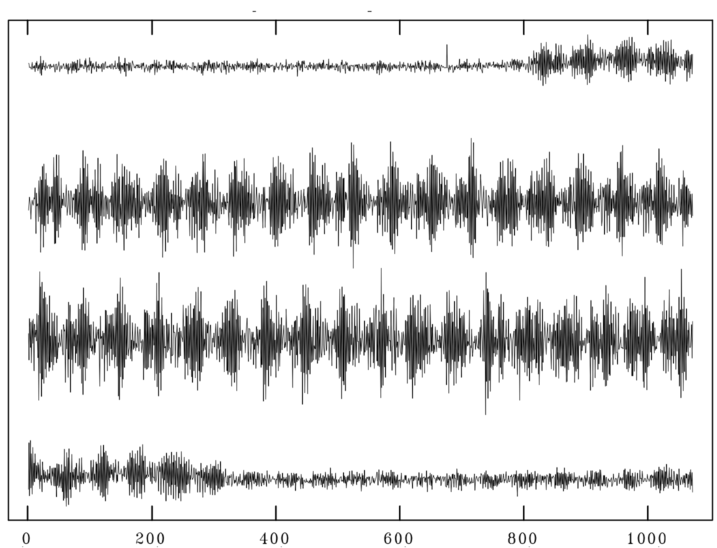


Fig. 3: The intensity profile of 4 rows inside a typical bright band. The repeating pattern exists for all rows in the image but is magnified in the bright bands**.**

Taking a cut across rows in the images shows a "wave packet" like variation in the intensity of the rows (**Fig. 3**); this variation was assumed to be the result of interference from within the spacecraft. Fourier analysis reveals that the frequencies of the interfering signals are roughly constant within a given (short exposure) image but that the frequencies differ from image to image. Longer exposure images (> ~ 10 seconds) do not show the wave packet appearance, but still exhibit significantly increased rms noise.

The interference has been traced to the power subsystem. Images taken during periods when the spacecraft is in the Earth's shadow (and is thus drawing from, instead of charging, the batteries) show neither increased noise nor the wave packet interference pattern.

The power system is unable to be modified on-orbit. Fourier-plane post-processing yields promising results for short-exposure images, but is ineffective for longer exposures. Firmware updates to the ROEs, to time the readout such that pixel values are read when interference is lowest, are being investigated. No results for this proposed fix have been obtained.

5. SATELLITE TRACKING EXPERIMENTS

At this point, the inability of the spacecraft to meet the spacecraft slewing and settling requirements has precluded satellite tracking R&D. Nonetheless, a handful of images with satellites in them have been obtained. Shown in **Fig. 4** is an image with a cluster of 3 Canadian and one American Geostationary satellites; this image was obtained in August 2014.

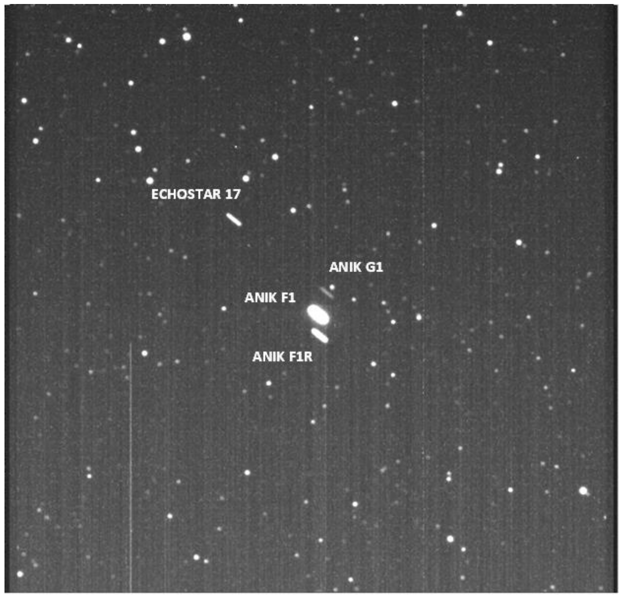


Fig. 4: The image of the first satellites intentionally imaged by NEOSSat. The cluster includes three satellites registered to Canada. Note that the image is inverted compared to other images in this paper.

In **Fig 5** is an image of a GPS satellite, also taken in August 2014. Only minimal processing was conducted on these images demonstrating that, even with the degraded CCD performance, NEOSSat still has the potential to deliver on many of its satellite metrics research goals once the slewing and stability issues have been dealt with.

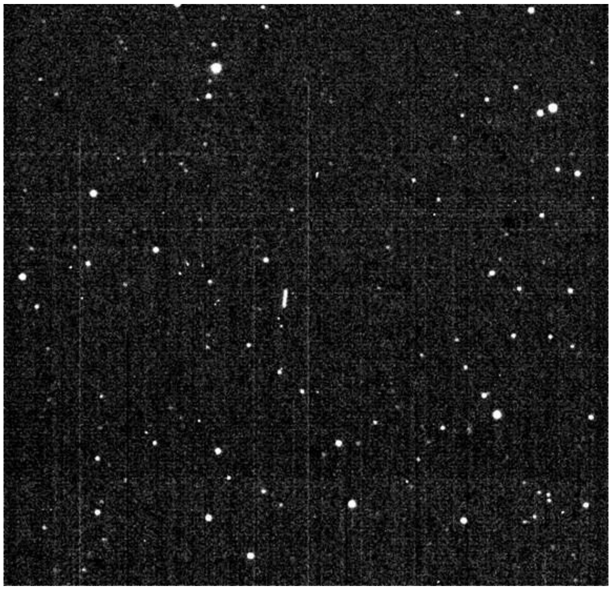


Fig 5: An image taken by NEOSSat of a GPS satellite; the satellite is the short near-vertical streak near the center of the image

6. CONCLUSION

As of late August 2014, the NEOSSat spacecraft is continuing in an extended commissioning phase. All spacecraft subsystems are working. The attitude control system is undergoing improvements to enable the required slewing and settling performance; the required pointing stability has been demonstrated. Improvements to the read-out electronics, to reduce the interference problem, are ongoing. Minimal targeted observing has been accomplished due to the evolving status of the ACS, and minimal characterization of the optics has been undertaken; the CCDs and the ROEs have been well characterized.

The imagery obtained by the spacecraft is marred by interference from the power subsytem; several potential mitigation strategies are being pursued. Approximately 1% of the pixels in the science CCD are consistently and anomalously bright, a number that is increases by roughly 25 pixels per day. A similar number of these "hot" pixels likely exist in the masked region of NEOSSat's frame transfer CCDs and are thought to be the cause of the vertical striping seen in the images.

NEOSSat has demonstrated the ability to obtain useful imagery of satellites. The NEOSSat satellite tracking team expects to be able to deliver on many of its research goals once the satellite achieves the required slewing and settling performance.

7. ACKNOWLEDGEMENTS

It is our pleasure to acknowledge the Operations team at the Canadian Space Agency, as well as the entire team at Microsat Systems Canada Inc. (MSCI, the prime contractor for NEOSSat) for the hard work and expertise that they have brought to the mission. Their dedication and professionalism is key to the success of NEOSSat.

8. REFERENCES

1. Scott, R.L., Wallace, B., Sale, M., Levesque, M., Thorsteinson, S., *Toward Microsatellite Based Space Situational Awareness*, Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, held in Wailea, Maui, Hawaii, September 10-13, 2013, Ed.: S. Ryan, The Maui Economic Development Board (http://www.amostech.com/TechnicalPapers/2013/International_Programs/SCOTT.pdf; accessed 30 Aug 2014)
2. NEOSSat Request for Proposals, Public Works and Government Services Canada Solicitation Number 9F006-051864/A, dated July 27 2006

3. Laurin, D., Hildebrand, A., Cardinal, R., Harvey, W., Tafazoli, S., *NEOSSat: a Canadian small space telescope for near Earth asteroid detection.* Proc. SPIE 7010, Space Telescopes and Instrumentation 2008: Optical, Infrared, and Millimeter, 701013 2008
4. Walker, G. et al., *The MOST Asteroseismology Mission: Ultraprecise Photometry from Space*, Publications of the Astronomical Society of the Pacific, 115:000 September 2003
5. Polidan, E.J., et al., *A study of hot pixel annealing in the Hubble Space Telescope Wide Field Camera 3 CCDs*, Proc. SPIE, Vol. 5487, 289, 2004
6. E2V CCD 47-20 product specification sheet, www.e2v.com/resources/account/download-datasheet/1427, accessed 30 August 2014